

# Software benchmarking

<http://bench.cr.yp.to>

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## Selecting cryptographic primitives

NIST's final AES report, 2001:

“Security was the most important factor in the evaluation . . .

Rijndael appears to offer an *adequate* security margin. . . .

Serpent appears to offer a *high* security margin.”

(Emphasis added.)

So why didn't Serpent win?

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So why didn't Serpent win?

Maybe hardware efficiency?

Or side-channel security?

Or something else?

Side channels: “The operations used by Serpent are among the easiest to defend against timing and power attacks.”

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Great! Why didn’t Serpent win?

Aha: Software speed!

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Conclusion: “NIST judged Rijndael to be the best overall algorithm for the AES. Rijndael appears to be consistently a very good performer in both hardware and software [and offers good key agility, low memory, easy defense, fast defense, flexibility, parallelism].”

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Will this factor alone decide the winner? Perhaps, but I doubt it! Many of the SHA-3 candidates seem extremely hard to break.

Presumably decision will depend partially on speed in software, speed in hardware, speed of implementations with various side-channel defenses, etc.

## Speed variability

Main question in this talk:

“How fast is hash software?”

Answer varies from  
one hash function to another.

Perhaps this variability  
is important to hash users.

Perhaps this variability will be  
important in the SHA-3 selection.

Answer depends on  
hash-function parameters.

On a 3200MHz AMD  
Phenom II X4 955 (100f42),  
changing from 256-bit output  
to 512-bit output makes

BMW  $\approx 1.96 \times$  faster;

Blake  $\approx 1.05 \times$  faster;

SIMD  $\approx 1.06 \times$  slower;

SHAvite-3  $\approx 1.45 \times$  slower;

ECHO  $\approx 1.71 \times$  slower;

Groestl  $\approx 2.06 \times$  slower.

Answer depends on #cores  
used for hashing.

2.4GHz Intel Core 2 Duo E4600  
(6fd) has 2 CPU cores  
operating in parallel.

2.4GHz Intel Core 2 Quad Q6600  
(6fb) has 4 CPU cores  
operating in parallel.

Hash twice as many  
messages per second!

Standard way to  
*reduce* this dependence:  
measure hash time on 1 core.

**Warning:** Single-core speed is sometimes better than speed of 4 cores handling 4 messages in parallel. Multiple active cores can conflict in DRAM access etc.

**Warning:** Single-core speed  $\times 4$  is usually better than speed of 4 cores cooperating to handle 1 long message.

**Warning:** These issues (and more issues coming up) have different effects on different hash functions.

Back to the main question:  
How fast is hash software?

Answer depends on CPU.

In one second, single-core  
1500MHz Intel Pentium 4 (f0a)  
computes SHA-512 hashes of  
9500 4096-byte messages.

In one second, single-core  
3192MHz Intel Pentium 4 (f43)  
computes SHA-512 hashes of  
21300 4096-byte messages.



Standard way to *reduce* this dependence: count cycles; i.e., divide #seconds by clock speed.

1500MHz Intel Pentium 4 (f0a):  
157924 cycles to hash a 4096-byte message with SHA-512.

3192MHz Intel Pentium 4 (f43):  
150128 cycles to hash a 4096-byte message with SHA-512.

Note: Most CPUs have built-in cycle counters; “RDTSC” etc.  
Cycles are also a natural unit for serious programmers.

**Warning:** Different CPUs do different amounts of computation in a cycle.

**Warning:** Different CPUs with different speeds can have the same name.

**Warning:** Some CPU operations (e.g. DRAM access) do not scale linearly with clock speed.

**Warning:** A CPU in 64-bit mode is often faster (but sometimes slower!) than the same CPU in 32-bit mode.

4096-byte SHA-512 timings:

53721 cycles: amd64 architecture  
(64-bit), 3000MHz Intel Core 2  
Duo E8400 (1067a).

80640 cycles: x86 architecture  
(32-bit), 3000MHz Intel Core 2  
Duo E8400 (1067a).

155304 cycles: 1900MHz Intel  
Pentium 4 (f12).

427760 cycles: 333MHz Intel  
Pentium 2 (652).

1352448 cycles: 416MHz ARM  
XScale-PXA270 rev 4 (v5l).

4096-byte SHA-256 timings:

64143 cycles: amd64 architecture  
(64-bit), 3000MHz Intel Core 2  
Duo E8400 (1067a).

65241 cycles: x86 architecture  
(32-bit), 3000MHz Intel Core 2  
Duo E8400 (1067a).

142580 cycles: 1900MHz Intel  
Pentium 4 (f12).

132342 cycles: 333MHz Intel  
Pentium 2 (652).

160576 cycles: 416MHz ARM  
XScale-PXA270 rev 4 (v5l).

# How fast is hash software?

Answer depends on message length: hashing long message takes more time than hashing short message.

SHA-512 timings on 3200MHz  
AMD Phenom II X4 955 (100f42):

55915 cycles for 4096 bytes.

29038 cycles for 2048 bytes.

15584 cycles for 1024 bytes.

8861 cycles for 512 bytes.

Standard way to

*reduce* this dependence:

divide cycles by message length.

**Warning:** Still have dependence.

SHA-512 on the same Phenom:

13.65 cycles/byte for 4096 bytes.

14.18 cycles/byte for 2048 bytes.

15.22 cycles/byte for 1024 bytes.

17.30 cycles/byte for 512 bytes.

21.34 cycles/byte for 256 bytes.

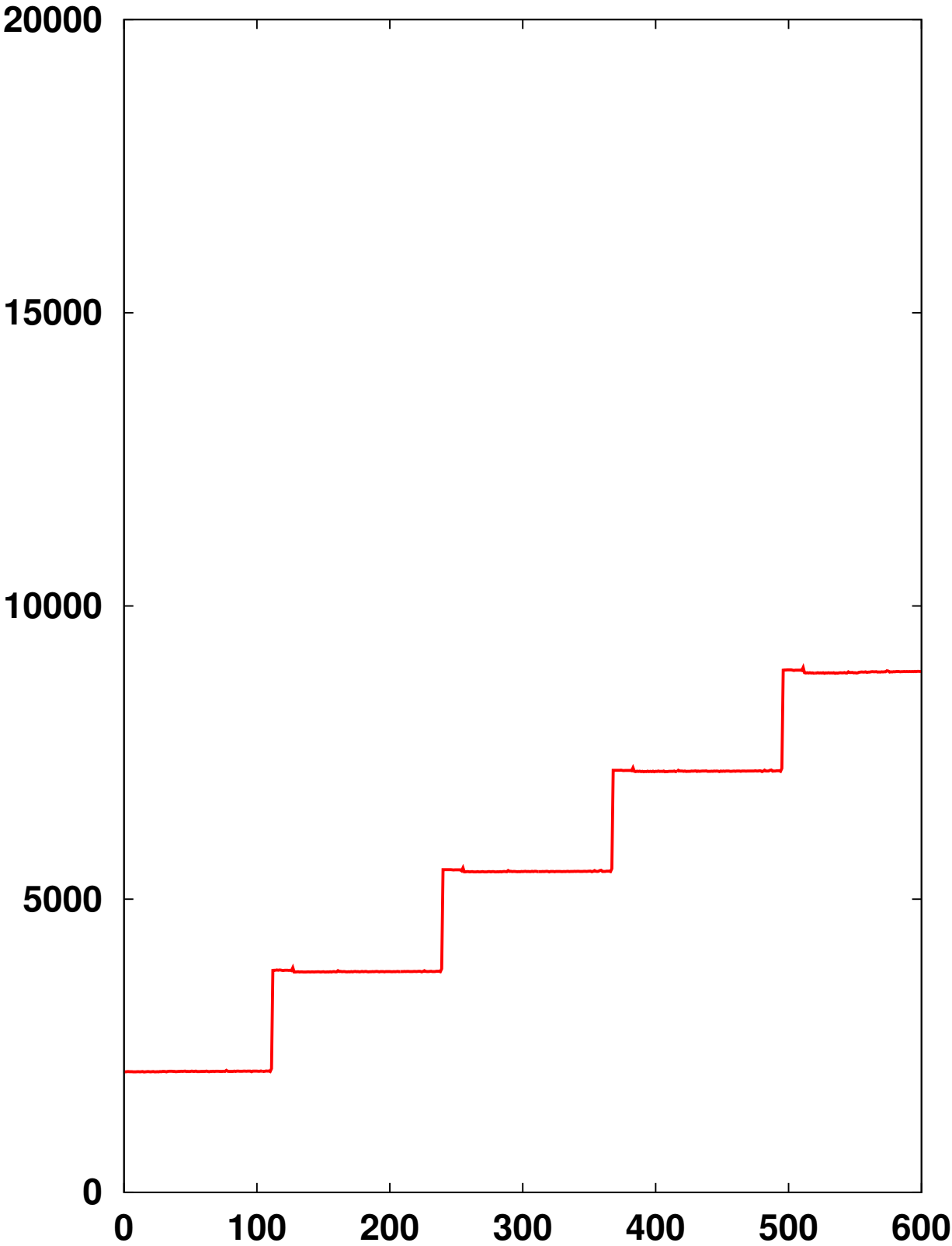
29.35 cycles/byte for 128 bytes.

33.80 cycles/byte for 112 bytes.

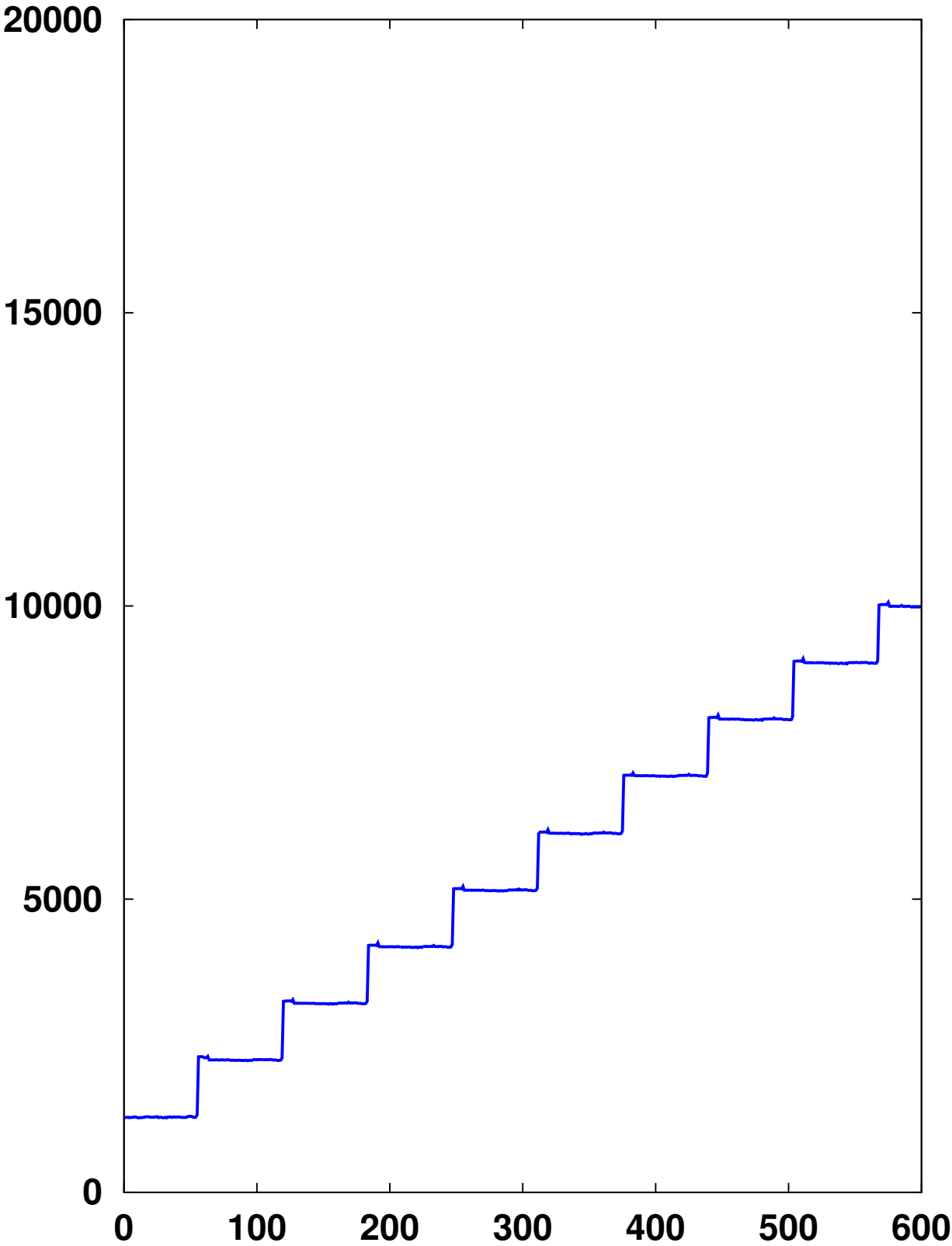
19.03 cycles/byte for 111 bytes.

32.15 cycles/byte for 64 bytes.

# SHA-512 cycles vs. bytes:

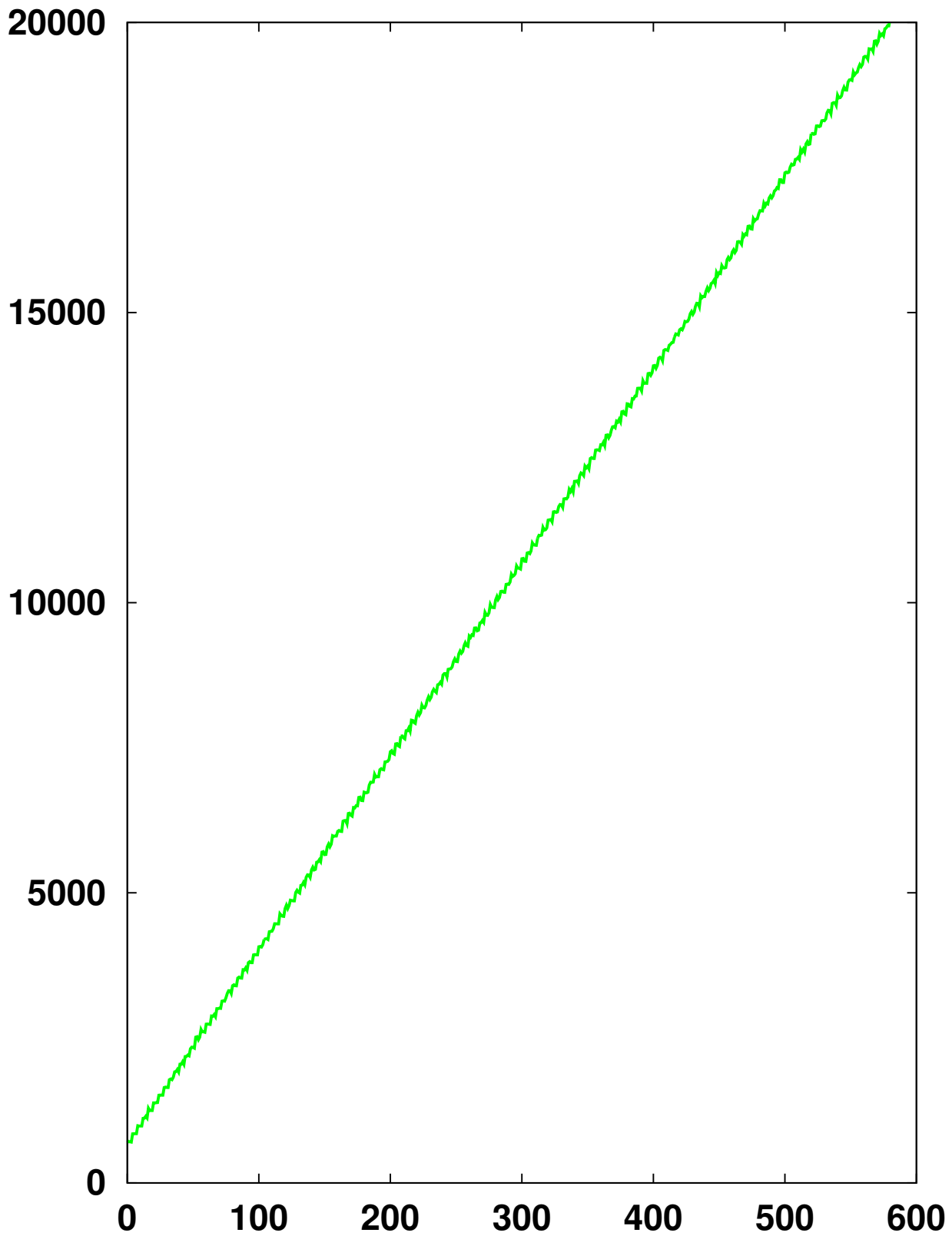


# SHA-256 cycles vs. bytes:

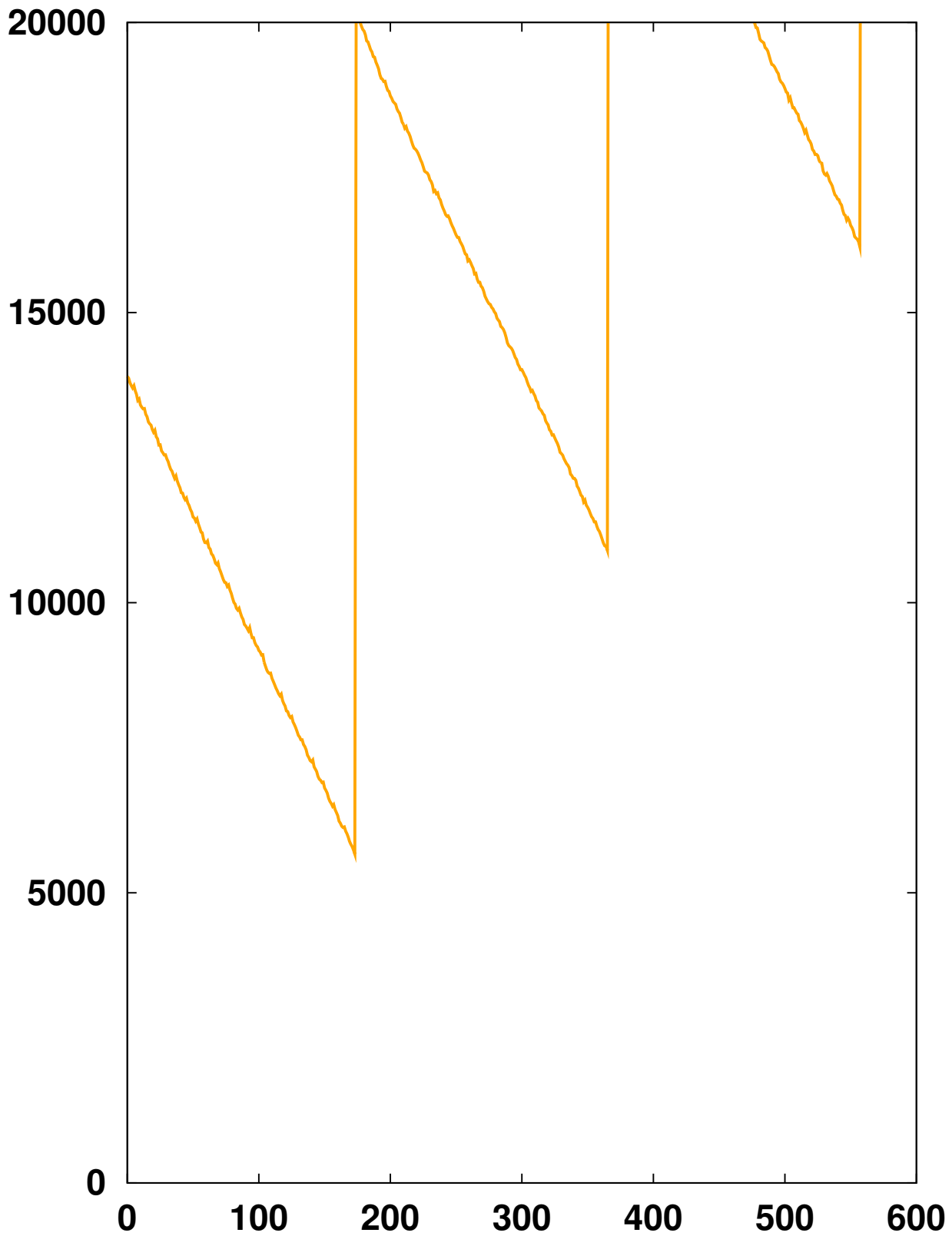




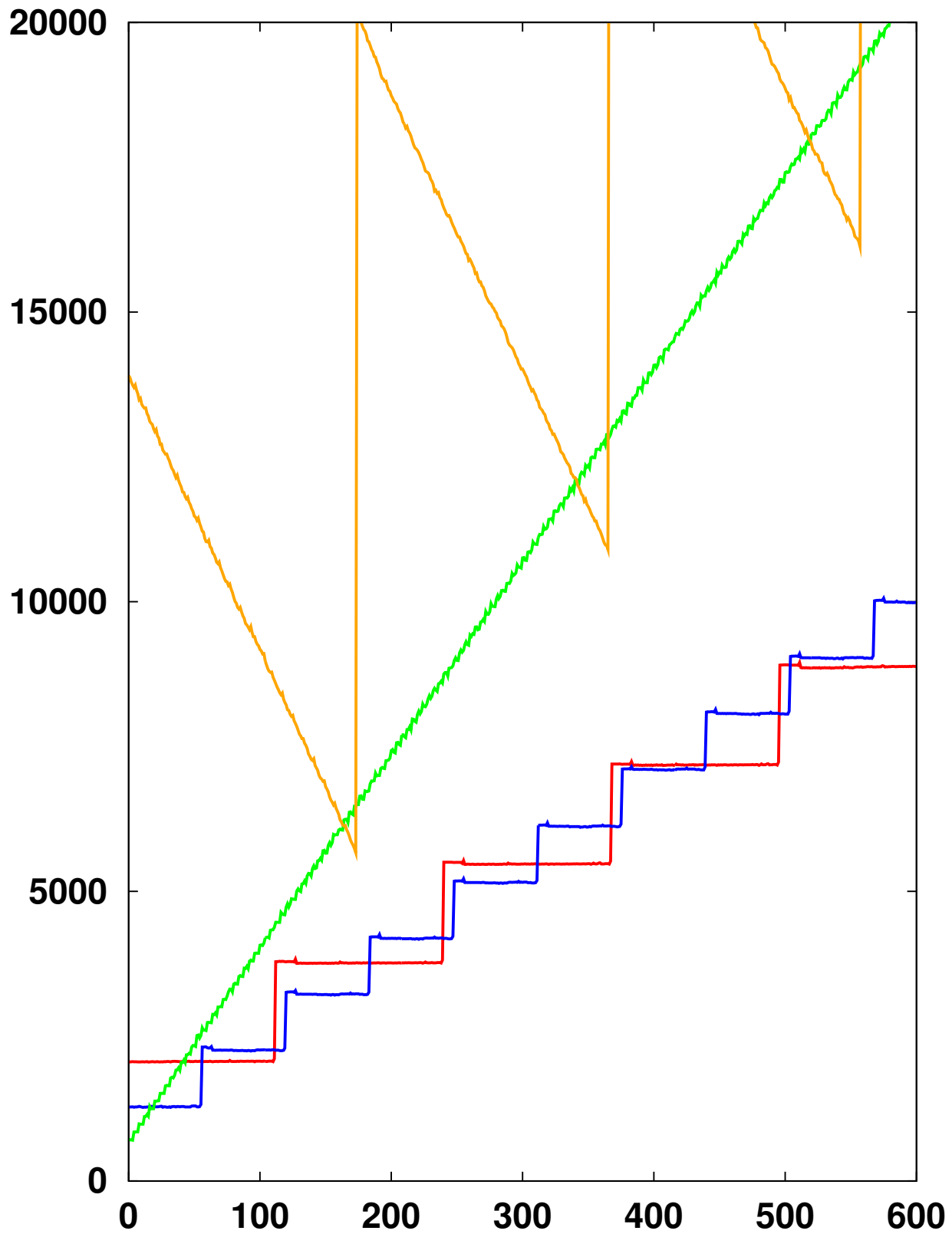
# Hamsi cycles vs. bytes:



# ECHO-256 cycles vs. bytes:



# Cycles vs. bytes:



# How fast is hash software?

Answer depends on implementation.

SHA-512: I wrote a simple reference implementation.

OpenSSL 0.9.8k is  $1.27\times$  faster than my implementation on a typical Core 2 (for 1536 bytes).

SIMD256: The “vect128” implementation is  $5.66\times$  faster than the “opt” implementation and  $247.99\times$  faster than the “ref” implementation.

A user who cares about speed won't use a slow reference implementation. He'll use the fastest implementation available.

Slowness of unused software has no impact on user's final speed.

The ultimate goal of benchmark reports is to accurately predict the speed that the user will see.

⇒ Report speed of the fastest implementation.

# How fast is hash software?

Answer depends on compiler  
and on compiler options.

SHA256, Core 2, 1536 bytes:

36824 cycles: `icc -O3 -static`

44840 cycles: `gcc -O`

`-fomit-frame-pointer`

48832 cycles: `gcc -O2`

`-fomit-frame-pointer`

**Warning:** There are many other effects on speed.

Answer depends on how much code is in cache.

Answer depends on how many table entries are in cache.

Answer depends on input/output alignment.

Answer depends on bytes being hashed.

Answer depends on details of timing mechanism.

# Benchmarking in the dark ages

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I’ll check the clock,  
10000 × hash 256 bytes,  
check the clock again,  
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Maybe more measurements:

“Oops, lots of overhead  
in hashing 256 bytes.  
I’ll try 4096 bytes.”

“Okay, 36.6 cycles/byte  
for SANDstorm-256  
on my 64-bit machine.

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How fast is SHA-2?”

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Traditional answer:

“I’ve written a SHA-256  
implementation too.

Let’s see . . . 39.1 cycles/byte.

SANDstorm is faster!

This is a *fair comparison*, because  
I wrote both implementations,  
and put similar effort into both,  
and measured both of them  
with my own timing tool.”

Reality: This SHA-256 software is embarrassingly slow.

SHA-256 users actually see much better performance.

To the SANDstorm designer:

You think that SANDstorm can be made faster too? Prove it!

There's nothing "unfair" about comparing best available code.

If SANDstorm *can't* run quickly: comparing lazy implementations makes SANDstorm look better than it actually is. Do we want to reward slow functions? Stupid!

Every dark-ages implementor  
builds his own timing tool.

Reports output as “Results”  
in an implementation paper.

Summary:

Cryptographic implementor  
is the benchmark implementor,  
the benchmark operator, and  
the competition’s misimplementor.

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Summary:

Cryptographic implementor  
is the benchmark implementor,  
the benchmark operator, and  
the competition’s misimplementor.

This pattern repeats for  
every cryptographic implementor.  
Hundreds (thousands?) of  
separate ad-hoc timing tools  
run on various hardware.

## Moving out of the dark ages

European Union has funded  
NESSIE project (2000–2003),  
ECRYPT I network (2004–2008),  
ECRYPT II network (2008–2012).

NESSIE's performance evaluators  
tuned C implementations  
of many cryptographic systems,  
all supporting the same API;  
wrote a benchmarking toolkit;  
ran the toolkit on 25 computers.

Many specific performance results:  
e.g., 24 cycles/byte on P4  
for 128-bit AES encryption.



ECRYPT I had five “virtual labs.”  
STVL, symmetric-techniques lab,  
included four working groups.  
STVL WG 1, stream-cipher group,  
ran eSTREAM (2004–2008).

De Cannière *published*  
eSTREAM benchmarking toolkit.

Stream-cipher implementations  
matching the benchmarking API  
were contributed by designers,  
*published*, often tuned;  
benchmarked on many computers.

e.g. 18 cycles/byte on P4 for  
third-party asm AES in toolkit.

2006: VAMPIRE, “Virtual Application and Implementation Lab,” started eBATS (“ECRYPT Benchmarking of Asymmetric Systems”), measuring efficiency of public-key encryption, signatures, DH.

*Published* a new toolkit.

Project is continuing.

Has written, collected, published 55 public-key implementations matching the benchmarking API. Benchmarked on many computers.

2008: VAMPIRE started eBASC  
(“ECRYPT Benchmarking  
of Stream Ciphers”) for  
post-eSTREAM benchmarks.

VAMPIRE also started eBASH  
(“ECRYPT Benchmarking  
of All Submitted Hashes”).

eBACS (“ECRYPT Benchmarking  
of Cryptographic Systems”)  
includes eBATS, eBASH, eBASC.  
Continues under ECRYPT II.

New toolkit, API; coordinated  
with CACE library (NaCl).

AES now 14 cycles/byte on P4.

Many advantages of eBACS  
over dark-ages benchmarking:

- >1000 compiler options.
- >100 machine-ABI pairs.
- Many message lengths.
- Very high reliability.
- Public verifiability.
- Real API, not only timing.
- Easy for implementor!

Today have 410 implementations.

Biggest disadvantage:

Report latency is high;

hard to use during development.

... but we're working on this.

eBASH → public

eBASH has already collected  
180 implementations of  
66 hash functions in 30 families.

[http://bench.cr.yp.to  
/results-hash.html](http://bench.cr.yp.to/results-hash.html)

already shows

measurements on 87 machines;  
124 machine-ABI combinations.

Each implementation is  
recompiled 1353 times  
with various compiler options  
to identify best working option  
for implementation, machine.

Online tables: medians, quartiles  
of cycles/byte to hash  
8-byte message,  
64-byte message,  
576-byte message,  
1536-byte message,  
4096-byte message,  
(extrapolated) long message.

Actually have much more data.  
e.g. Reports show best options.  
e.g. Graphs show medians for  
0-byte message, 1-byte message,  
2-byte message, 3-byte message,  
4-byte message, 5-byte message,  
... , 2048-byte message.

## Implementor → eBASH

Define output size in `api.h`:

```
#define CRYPTO_BYTES 64
```

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Define hash function in `hash.c`,  
e.g. wrapping existing NIST API:

```
#include "crypto_hash.h"  
#include "SHA3api_ref.h"  
int crypto_hash(  
    unsigned char *out,  
    const unsigned char *in,  
    unsigned long long inlen)  
{ Hash(crypto_hash_BYTES*8  
        ,in,inlen*8,out);  
    return 0; }
```



Send to the mailing list  
the URL of a tar.gz  
with one directory  
crypto\_hash/yourhash/ref  
containing hash.c etc.

Measurements magically appear!  
Much easier than trying  
to do your own benchmarks.

More details and options:  
[http://bench.cr.yp.to  
/call-hash.html](http://bench.cr.yp.to/call-hash.html)

You can implement  
someone else's function  
and show off how cool you are!

Example:

eBASH includes BLAKE speedups  
from Peter Schwabe  
and from Samuel Neves.

We'd like to see all second-round  
SHA-3 candidates covered by  
good implementations.

Contact us for coordination.